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Keywords
Closed–loop supply chain, Network design, Carbon emission, Regulatory policy

Disciplines
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Abstract

This paper considers a closed–loop supply chain (CLSC) network design problem that accounts for the impact of carbon emission regulations. Three regulatory policy settings are considered; namely, (a) firms are subject to mandatory carbon caps on the amount of carbon they emit, (b) firms are taxed on the amount of emissions, and (c) firms can participate in a carbon cap and trade system. Traditional CLSC network design models are extended to account for the carbon emissions caused by transportation under different transportation modes. Model validations are demonstrated via a case study. Through detailed sensitivity analysis, we investigate how the parameters of regulatory emission control policies affect aspects of the CLSC network design such as product allocation and transportation configuration. This new formulation provides the decision makers with tools to balance the trade-offs between usual costs and the impact of carbon emission regulations. It also highlights the significance of incorporating carbon emission considerations when designing the CLSC network.

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1. Introduction
Global climate change is one of the most important issues facing the world today. It is a general consensus that carbon dioxide emissions are a significant contributor to global warming and climate change. Under great pressure to reduce emissions, many government regulations such as the Kyoto protocol have been established. Control of carbon emissions is becoming inevitable. The European Union has already implemented the carbon emission trading scheme (EU ETS) for the energy-intensive industries. Similar schemes are coming across the United States in various states or regions and in other major countries.

Firms in different industries should expect there to be penalties for their carbon emissions and those changes will force the firms to take an entire new perspective on their supply chain management. Current research suggests that the firm's forward supply chain may need to be redesigned under carbon emission regulations [1]. But companies nowadays inevitably face activities in the reverse supply chain such as returns management, recycling and remanufacturing or refurbishing [2]. For example, the annual costs of commercial returns exceed 100 billion [3]. Therefore, it is necessary for the firm to take a closed-loop supply chain perspective, which includes both forward supply-chain activities and the additional activities of the reverse supply chain into consideration, when coordinating their carbon management and supply chain management.

In this paper we focus on developing a mathematical model for closed-loop supply chain (CLSC) network design with carbon emission considerations. Under such regulations, firms who participate in CLSC activities can reduce their emissions by remanufacturing activities, but transportation of the used or returned products will increase the firm's carbon emission. Therefore, CLSC network design under emission regulations will become critical issues for them. We show that different carbon emission regulations have different impacts on the network configuration. Moreover, firms should look carefully at all of the cost and carbon parameters when designing the network of closed-loop supply chain. The remainder of the paper is organized as follows: Section 2 provides a literature review; Section 3 presents the mathematical formulation of the model; Section 4 provides a numerical analysis of the model; and Section 5 presents the key observations of this paper. Section 6 concludes.

2. Literature Review

Closed-loop supply chain management focuses on the design, control, and operation of a system to maximize value creation over the entire life cycle of a product including recovery of value from different types and volumes of returns over time [4]. Network design for CLSC has attracted the attention of a growing number of researchers in the past decade (see [5] for a complete review). Various methods have been developed to establish an optimal infrastructure to manage both forward and reverse channels in a coordinated manner. As various carbon emission regulations are taking effect, many researchers are interested in how those regulations would affect firm's supply chain management strategy. Reference [6] presents a mathematical programming model for environmentally conscious supply chain network design with the explicit inclusion of carbon emission cost. Ramudhin et al. [7] introduce a mixed integer programming (MIP) formulation of the green supply chain network problem. Their model focuses on the impact of transportation, subcontracting, and production activities on the design of a green supply chain. Diabat and Simchi-Levi [8] introduce a new supply chain network problem with a carbon emission as a mandate constraint. They find that the supply chain total cost increases as the carbon emission allowance decreases. All the previous research provides useful insights for coordinating carbon emissions within the supply chain management, but fails to take the reverse activities into account. Also, as the previous work focuses on the impact of subcontracting and production activities with a predetermined supply chain network, the effect of carbon regulations on the network configuration is not addressed. In this paper, we will develop an integrated model for CLSC network design with the consideration of carbon emissions. To the best of our knowledge, it is the first paper that considers carbon regulation explicitly in CLSC design.

3. Mathematical Model Formulation

In this paper, we characterize the decision of facility location and choice of transportation mode. We also consider the manufacturer's return policy for new products because it has a significant impact on the amount of returns. We consider that there are not only demands for new products but also demand for the returned products. We assume that the company has a total deterministic demand for the returned product. Such demand is generated either from a consumer's order or internal demand within the company. We then use the following model to capture the impact of carbon emission regulations on the optimal CLSC structure. We only consider the emissions that are generated from transportation, and we assume that there are no emissions associated with ordering or holding products in inventory. Also, the emissions related to the construction and maintenance of the facilities are not considered. We use the following notation.

Sets and indices

$I = \{1, \ldots, N_p\}$ potential factories for manufacturing new and recovering used products
$J = \{1, \ldots, N_w\}$ potential warehouses for distribution of new products
$L = \{1, \ldots, N_c\}$ potential collection centers for returned products
$K = \{1, \ldots, N_k\}$ consumer's location
$M = \{1, \ldots, N_m\}$ potential transportation modes
$R = \{1, \ldots, N_r\}$ possible return policies for new product

Parameters

$c_{ij}^m, c_{jk}^m, c_{kl}^m, c_{li}^m$ unit cost of demand served from facility i to warehouse j, warehouse j to customer k, consumer k returns to facility l, facility l returns to factory i using transportation mode m, $i \in I$, $j \in J$, $k \in K$, $l \in L$, $m \in M$
c_k^u, c_k^r unit cost of customer k non-satisfied demand and uncollected return, $k \in K$
c^r unit cost of non-satisfied demand for returned products (at the factory)
f_i^p, f_j^w, f_l^c fixed cost of opening factory i, warehouse j, collection center l, $i \in I$, $j \in J$, $l \in L$
α^m carbon emission factor per unit distance due to the use of transportation mode m, $m \in M$

d_k^n, d^r new product demand of customer k, $k \in K$, and total demand for returned product
λ_{kr} percentage returns from customer k under return policy r, $r \in R$
ω_r unit refund under return policy r, $r \in R$

Decision Variables

X_{ij}^m products shipped from factory i to warehouse j using transportation mode m, $i \in I$, $j \in J$, $m \in M$
X_{jk}^m demand served by warehouse j to customer k using transportation mode m, $j \in J$, $k \in K$, $m \in M$
X_{kl}^m quantity of returns from consumer k to collection center l using mode m, $k \in K$, $l \in L$, $m \in M$
X_{li}^m quantity of returns from collection center l to factory i using mode m, $l \in L$, $i \in I$, $m \in M$
U_k, W_k unsatisfied demand and uncollected return of customer k, $k \in K$
U unsatisfied demand of returned product (factory)
$Y_i^p, Y_j^w, Y_l^c = 1$ if facility i, j or l is opened $i \in I$, $j \in J$, $l \in L$
$Y_r = 1$ if return policy r for new product is applied, $r \in R$

We first introduce a generic network design problem for CLSC without considering carbon emissions. Then, we will consider several regulatory policies to incorporate carbon emission concerns. Such regulatory policies include: (1) mandatory caps on the amount of carbon emitted by transportation. (2) tax on the amount of transportation emissions. (3) imposition of a cap–and–trade system for transportation-induced carbon emissions.

4. CLSC Network Design Problem without Emission Concerns

The model for a generic network design problem for CLSC without carbon emission considerations is as follows.

$$\min z = \sum_{i\in I} f_i^p Y_i^p + \sum_{j\in J} f_j^w Y_j^w + \sum_{l\in L} f_l^c Y_l^c + \sum_{i\in I}\sum_{j\in J}\sum_{m\in M} c_{ij}^m X_{ij}^m + \sum_{j\in J}\sum_{k\in K}\sum_{m\in M} c_{jk}^m X_{jk}^m$$
$$+ \sum_{k\in K}\sum_{l\in L}\sum_{m\in M} c_{kl}^m X_{kl}^m + \sum_{l\in L}\sum_{i\in I}\sum_{m\in M} c_{li}^m X_{li}^m + \sum_{k\in K} c_k^u U_k + \sum_{k\in K} c_k^w W_k + c^r U + \sum_{k\in K}\sum_{r\in R} \omega_r Y_r \lambda_r (d_k^n - U_k)$$

The objective function (z) to minimize is the total cost. The first three terms refer to the fixed cost for opening corresponding facilities. The fourth to seventh terms correspond to the variable cost between factories and warehouse, warehouse and consumers, consumers and collection centers, collection centers and factories, respectively. The last four terms represent the penalty cost of not satisfying the total customer demand and returns, the factory demand for returned products and consumer refunds. The following constraints must be satisfied.

$$\sum_{j\in J}\sum_{m\in M} X^m_{jk} + U_k = d^n_k, \forall k \in K \quad (1)$$

$$\sum_{l\in L}\sum_{m\in M} X^m_{kl} + W_k = \sum_{r\in R} Y_r \lambda_r (d^n_k - U_k), \forall k \in K \quad (2)$$

$$\sum_{l\in L}\sum_{i\in I}\sum_{m\in M} X^m_{li} + U \geq d^r \quad (3)$$

$$\sum_{i\in I}\sum_{m\in M} X^m_{ij} = \sum_{k\in K}\sum_{m\in M} X^m_{jk}, \forall j \in J \quad (4)$$

$$\sum_{i\in I}\sum_{m\in M} X^m_{li} = \sum_{k\in K}\sum_{m\in M} X^m_{kl}, \forall l \in L \quad (5)$$

$$\sum_{k\in K}\sum_{l\in L}\sum_{m\in M} X^m_{kl} \leq \sum_{j\in J}\sum_{k\in K}\sum_{m\in M} X^m_{jk} \quad (6)$$

$$\sum_{j\in J}\sum_{m\in M} X^m_{ij} \leq G Y^p_i, \forall i \in I \quad (7)$$

$$\sum_{k\in K}\sum_{m\in M} X^m_{jk} \leq G Y^w_j, \forall j \in J \quad (8)$$

$$\sum_{i\in I}\sum_{m\in M} X^m_{li} \leq G Y^c_l, \forall l \in L \quad (9)$$

$$\sum_{l\in L}\sum_{m\in M} X^m_{li} \leq G Y^p_i, \forall i \in I \quad (10)$$

$$\sum_{r\in R} Y_r = 1 \quad (11)$$

$$Y^p_i, Y^w_j, Y^c_l, Y_r \in \{0,1\}, \forall i \in I, \forall j \in J, \forall m \in M, \forall l \in L, \forall r \in R \quad (12)$$

$$X^m_{ij}, X^m_{jk}, X^m_{kl}, X^m_{li} \geq 0, \forall i \in I, \forall j \in J, \forall m \in M, \forall l \in L \quad (13)$$

Constraints (1) and (2) ensure that all consumers' demand and returns are taken into account. Constraint (3) ensures that the factory's demand for returned product is satisfied. Constraints (4) and (5) ensure that the warehouse and collection centers will not create stocks. Constraint (6) ensures that the amount returned by all collection centers must be less than the amount produced by all factories. Constraints (7) to (10) are common disjunctive constraints, where G is a very large positive number. Constraint (11) ensures that the manufacture can choose exactly one return policy for new products. We should notice that introducing constraint (2) and the last term of the objective makes the model non–linear. We can solve it as a linear model by decomposing this constraint into several different scenarios based on constraint (11).

Strict Carbon Caps. Under this setting, the firm is subject to a fixed cap C on transportation-caused emissions. To address the concerns of carbon emission, we define the total carbon emissions (E^T) as:

$$[illegible] \quad (14)$$

The following carbon cap will be included as a constraint.

$$E^T \leq C \quad (15)$$

The emission factors (e^m) can be identified from previous research, where truck has an emission factor 187 (grams/ton-mile), rail (intermodal) has an emission factor 40 (grams/ton-mile) and air (Boeing 747–400) has an emission factor 1,385 (grams/ton-mile) [9]. Moreover, we assume the weight of 10,000 units of the product is 1 ton.

Carbon Tax. If the regulatory party uses a penalty scheme such as imposing a tax according to the grams of carbon emitted, we need only to change the objective function to $\min z + \mu E^T$, which subject to constraints (1) to (13). Here, μ denotes the amount of tax paid on each unit emitted, and *z* is the original objective function.

Cap–and–Trade system. The "cap–and–trade" system allows companies to buy emissions credits from those who emit less in order to meet their emissions limit or cap, which usually imposed by the regulatory party. Companies can also sell their emission allowances if their emission is below the cap. If we assume the price of carbon allowances is exogenously determined, we can reformulate the problem as follows:

$$\min z + \phi(e^+ - e^-) \quad (16)$$

$$s.t.\ E^T + e^- \leq C + e^+, \ e^+, e^- \geq 0 \quad (17)$$

along with constraints (1) to (13). e^+ and e^- denote the number of carbon credits the firm buys and sells, respectively, with carbon price ϕ.

5. Case Study

We will analyze a case from an earlier paper to illustrate how the carbon emission regulations might affect the CLSC network design. This is example based on a document–office company that operates in the Iberian market [10]. In this case study, there are five potential locations for producing new products and remanufacturing returned products, eight locations for warehouses and five locations for collection centers. The number of consumers is 15. We use uniform distributions to generate data for parameters. The fixed cost of opening a factory, warehouse and collection center are generated from *U*[3200,5500], *U*[800,1200] and *U*[5000,7200], respectively. Those data are also based the examples in [10]. The unit cost can be calculated by the following equations: [illegible], [illegible], [illegible], [illegible], where [illegible], [illegible], [illegible] and [illegible] are distance between nodes i and j, j and k, [illegible] and l, l and i, respectively. The unit transportation cost [illegible] is 0.2, 0.04, 1.4, respectively, for railway, trucks and air, while [illegible] is 0.7, 0.1, 5. [illegible] is 0.5, 0.08, 4. [illegible] is 0.4, 0.08, 3. The demand for return product is generated from *U*[3200,3400]. Non-satisfied demand penalty is generated from *U*[600,1200], and the demand for new product is generated from *U*[700,2000]. The penalty for uncollected returns is generated from *U*[500,800]. The amount of non-satisfied return for the factory is generated from *U*[700,9000]. The percentage of returns and unit refund, respectively, under return policy R1 are 0.05 and 7, under R2 are 0.13 and 8.5, and under R3 are 0.2 and 9.5. All the instances are solved by the ILOG CPLEX 11.0 MIP solver in GAMS within 0.09s and all tests are carried out on a Pentinum dual-core 3.20 GHz computer with 3 GB RAM. We first solve the model without emission considerations. The total cost is 82079.2, and the total emission is 1733.1. Facilities (I2 I3 I4 I5 K1 K3 K5 K6 C1 C2 C4 C5) are not used, and return policy 3 is used for new product. The network configuration is shown in Figure 1.

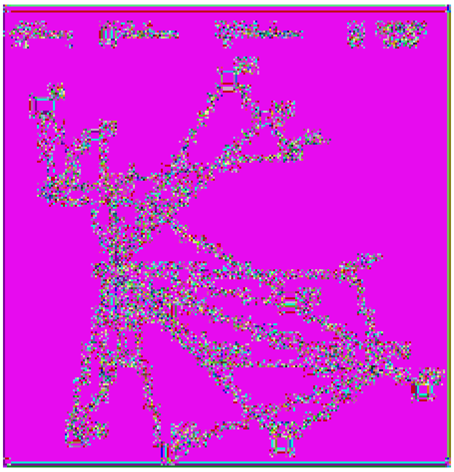

Figure 1. Network configuration for basic problem

Carbon Cap. The results for the total cost and total emission are shown in Figure 2 (a). The impact of carbon cap on network configuration and return policy is shown in Table 1. We can see from the table that the mandatory cap has an intense impact on the configuration of the network, and the total cost decreases as the cap increases.

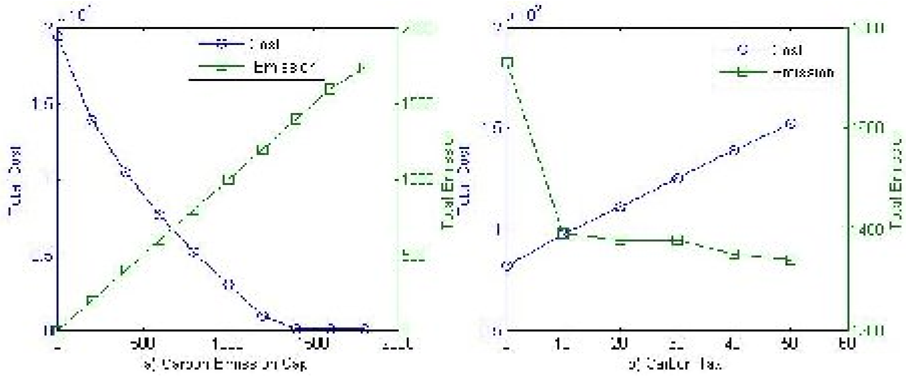

Figure 2. The impact of carbon cap and carbon tax on total cost and total emission

Table 1: Impact of carbon cap on network configuration

Carbon Cap	Facility not used	Return policy
0	All	R1
200	I3 K1 K3 K5 K6 C2 C4	R1
400	I3 K1 K3 K5 K6 C2	R1
600	I3 K1 K3 K6 C2	R1
800	I3 K1 K3 K6	R1
1000	I3 K1 K3 K6	R2
1200	I3 K1 K3 K6	R3
1400	I3 I5 K1 K3 K5 K6 C2 C4	R3
1600	I2 I3 I5 K1 K2 K5 K6 C2 C4 C5	R3
1800	I2 I3 I4 I5 K1 K3 K5 K6 C1 C2 C4 C5	R3

Carbon Tax. The results for the total cost and total emission are shown in Figure 2 (b). The total cost is approximately linearly increasing in the carbon tax. The impact of carbon tax on network configuration and return policy is shown in Table 2.

Table 2: Impact of carbon tax on network configuration

Carbon Tax	Facility not used	Return policy
0	I2 I3 I5 K1 K3 K5 K6 C1 C2 C4 C5	R3
10	I3 I5 K1 K3 K5 K6 C2 C4	R3
20	I3 I5 K1 K3 K5 K6 C2 C4	R3
30	I3 I5 K1 K3 K5 K6 C2 C4	R3
40	I3 I5 K1 K3 K6 C2 C4	R3
50	I3 I5 K1 K3 K6 C4	R3

Carbon Cap and Trade System. The results for the total cost and total emissions under carbon cap and trade system is shown in Figure 3. The network configuration and return policy will not change compared with carbon tax, but the firm will buy 233.1 carbon credits when the price is 0, and sell 203.0, 108.5, 31.5 carbon credits when carbon price is 5, 10, 15-30, respectively .

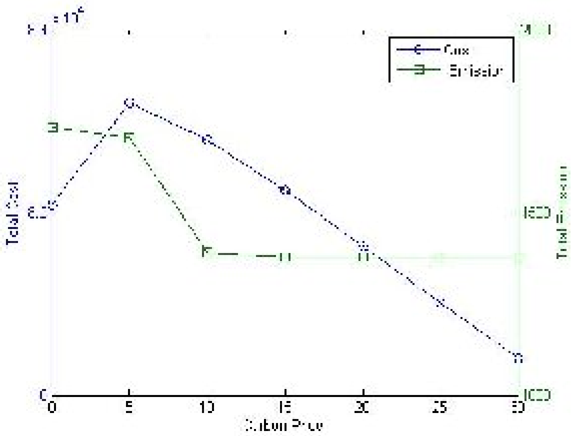

Figure 3. The impact of carbon price on total cost and total emission (Cap = 1500)

5.1 Observations

Observation 1: The carbon emission regulations have more impact on firms' network configuration when firms participate less in closed--loop supply chain activities.

Under our setting, the network configurations are more sensitive to the emission regulation. Under carbon tax and cap–and–trade system, the cost of carbon will account for a larger proportion of total cost. Therefore, the configuration will be adjusted according to the total cost.

Observation 2: Higher tax or carbon price may not necessarily lead to a lower carbon emission.

From the Figures we can see that the total emissions are more sensitive to certain levels of tax or price, which means that a higher tax may not necessarily lead to a lower emissions.

Observation 3: A cap-and-trade system can reach a desired level of emissions while imposing the least total cost comparing to mandatory cap and carbon tax. Compared to carbon tax, cap-and-trade system will not change the configuration of the supply chain network.

Under the cap–and–trade system, constraint (16) is always binding. The objective function then changes to $\min z + \alpha T^{tc} - \alpha C$. The configuration of the network will not be affected but the total cost will decrease.

Observation 4: A cap--and--trade system and carbon tax policy will not affect a firm's return policy but a tighter carbon cap will change the return policy.

A tighter carbon cap will impose a strong constraint on the firm’s carbon emission. The only way that the firm can satisfy the emission constraint is to participate less in the reverse activities.

Observation 5: Under a higher carbon tax rate and higher carbon price, more facilities will be used.

Under cap–and–trade system, the total amount of carbon emission will decrease when more facilities are used. So when the carbon tax rate or carbon price is high, opening more facilities will be optimal.

Observation 6: Railway transportation mode will be used if carbon emission regulations are taken into account.

As the railway has the lowest emission factor, if carbon emission regulations are taken into account, railway transportation will always be preferred.

6. Conclusion

The main contribution of this paper is the development of an integrated model for CLSC network design under different carbon emission regulatory policies. Using the model, supply chain managers are now able to assess the impact of different carbon emission regulations on CLSC operations. The application of the model can show how the closed loop supply chain network may balance the trade–offs between the carbon emission and total costs. Based on our numerical examples, we obtain several observations regarding the network configuration and the impact of different regulation policies. We find that mandatory cap has the most significant impact on the network configuration while a cap–and–trade system can reach the desirable level of carbon emission with the least cost. Moreover, a carbon cap will also change the firm’s return policy for new product while the other two policies will not. In terms of transportation mode, railway will be preferred as it has the lowest emission factor. Based on our results, we suggest that CLSC network design must integrate the consideration of carbon emission regulation to balance the trade-offs between cost and emissions. In future work, the model can be extended to incorporate the carbon emissions from producing the product and constructing the facilities.

References

1. Benjaafar, S., Li, Y. and Daskin, M. "Carbon Footprint and the Management of Supply Chains: Insights from Simple Models," Working Paper, Department of Mechanical Engineering, University of Minnesota, 2009.
2. Guide, V. Daniel R., J., Souza, G. C., Van Wassenhove, L. N. and Blackburn, J. D., "Time Value of Commercial Product Returns," Management Science, 2006, 52, 1200-1214.
3. Atasu, A.., Guide Jr, V. and Wassenhove, L. "Product Reuse Economics in Closed-Loop Supply Chain Research," Production and Operations Management, 2008, 17, 483-496.
4. Van Wassenhove, L. "The Evolution of Closed-Loop Supply Chain Research," Operations Research, 2009, 57, 10-18.
5. Akcali, E., Cetinkaya, S., and Uster, H, "Network Design for Reverse and Closed-Loop Supply Chains: An Annotated Bibliography of Models and Solution Approaches," Networks, 2009, 53, 231-248.
6. Chaabane, A., Ramudhin, A., Paquet, M., and Benkaddour, M., "An Integrated Logistics Model for Environmental Conscious Supply Chain Network Design," Proceedings of AMCIS 2008, 2008, 175-187.
7. Ramudhin, A., Chaabane, A.; Kharoune, M., and Paquet, M. "Carbon Market Sensitive Green Supply Chain Network Design," Proceedings of 2008 IEEE International Conference on Industrial Engineering and Engineering Management, 2008, 1093-1097.
8. Diabat, A. and Simchi-Levi, D. "A Carbon-Capped Supply Chain Network Problem," Proceedings of 2009 IEEE International Conference on Industrial Engineering and Engineering Management, 2009, 523-527.
9. Facanha, C. and Horvath, "An Evaluation of Life-Cycle Air Emission Factors of Freight Transportation," Environmental Science & Technology, 2007, 41, 7138-7144.
10. Salema, M., Póvoa, A. and Novais, A. "A Warehouse-Based Design Model for Reverse Logistics," Journal of the Operational Research Society, 2005, 57, 615-629.